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ABSTRACT

Science education has received increasing attention during the 1980s in both professional and public forums. This paper addresses three questions having to do with science teaching. The first question concerns student learning in science classes. The document proposes that science achievement is generally disappointing, especially if student understanding is evaluated rather than rote memorization. Four learning activities are presented and discussed for the purpose of indicating that many student difficulties can be attributed to the fact that science learning is a complex and difficult process of conceptual change. The second question addressed concerns science teachers' skills and preparation. A synthesis of recent studies describes some of the essential skills and knowledge that teachers need to teach successfully for conceptual change to occur in students. Unfortunately, the data indicates that most elementary and secondary school teachers lack important components of those skills and knowledge. The third question concerns how science teaching can be improved, and in the last part of the paper a variety of possibilities for improving science education through professional development and improvements in curriculum materials is discussed. An annotated bibliography is included. (Author/TW)

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TEACHING SCIENCE

Charles W. Anderson and Edward L. Smith

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Co-Directors: Jere E. Brophy and Andrew C. Porter

Associate Directors: Judith E. Lanier and Richard S. Prawat

Editorial Staff
Editor: Sandra Gross
Assistant Editor: Sally B. Pratt

Abstract

This paper addresses three questions having to do with science teaching. The first question concerns student learning in science classes. Science achievement is generally disappointing, especially if student understanding is evaluated rather than rote memorization. Many student difficulties can be attributed to the fact that science learning is a complex and difficult process of conceptual change. The second question concerns science teachers' skills and preparation. A synthesis of recent studies describes some of the essential skills and knowledge that teachers need to teach successfully for conceptual change in students. Unfortunately, most elementary and secondary school teachers currently lack important components of those skills and knowledge. Finally, a variety of possibilities for improving science education through professional development or improvements in curriculum materials are discussed.

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TEACHING SCIENCE[1]

Charles W. Anderson and Edward L. Smith[2]

Introduction

Science education has received increasing attention over the past few years in both professional and public forums. This attention has tended to focus on two related issues. First, we need to know *more* science than we used to, whether the concern is with coping with an increasing role of technology in our daily lives, protecting our health, preparing and competing for jobs, or exercising responsible judgment as a citizen; however, it seems that as a nation we actually know *less* science than we used to. Declines in standardized test scores, lack of preparedness on the part of individuals or groups of students, and unfavorable comparisons between American students and those of other nations are well cited as indications that our schools are failing to prepare students adequately for current or future needs.

In this chapter we will discuss both the evidence that gives rise to these concerns and possible solutions to our current problems. We will begin by describing three major areas of concern that are shared by science teachers, science educators, and the general public: (a) How well are our students learning science? (b) How competent and well prepared are our science teachers? (c) How can we best improve science teaching in our schools? We will describe the general nature of each concern and define specific questions that can be illuminated by available research findings.

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[1]This chapter appeared in V. Koehler (Ed.) (1985). The educator's handbook: A research perspective. New York: Longman.

[2]Charles W. Anderson and Edward L. Smith are coordinators of the Science Teaching Project and both are associate professors of teacher education at Michigan State University.

Our discussion will draw upon two distinct bodies of research. The first looks at science education on a nationwide scale. This includes a series of studies and reports from the National Science Foundation's Status Studies (Helgeson, Blosser & Howe, 1977; Weiss, 1978; Stake & Easley, 1978) to the report of the National Commission on Excellence in Education (1983). These studies have been influential in creating awareness of problems in science education. They identify the extent of the problems and reflect a variety of proposed directions for solution; however, they do not provide very much new understanding of the underlying nature of the problems.

The best insight into the mechanisms that allow these problems to persist and the best ideas for improvement come from a second body of research, consisting mostly of studies conducted in a few classrooms or with only a few individual students. For each of the three concerns defined above, we will identify both questions that can be addressed by the status studies and questions that can be addressed by the research on teaching and learning.

How Well Are Our Students Learning Science?

Educators, scientists, and others have expressed concern about claims of growing scientific and technological illiteracy at a time of unprecedented need for increased scientific and technological sophistication in our workers and citizens. Research on science education can help us to understand this problem in two ways. First, it can document the nature and extent of the problem. Which of our students are learning about science? How much are they learning? Where is their knowledge deficient? Second, science education research can help us to understand some of the origins of these problems. What makes science difficult for students to learn? What kinds of difficulties do

students encounter? How does successful science learning occur? These questions will be addressed below.

How Competent and Well Prepared Are Science Teachers?

The status studies provide information about teachers' personal judgments about their competence and preparation and also about the degree to which teachers meet conventional standards of academic preparation. Classroom research on the teaching and learning of science enables us to investigate teacher competence and preparation at a deeper level: What does it mean to teach science effectively? What are the characteristics of teaching which succeed in promoting science learning in classrooms? What do teachers *do* that accounts for this effectiveness? Finally, what do effective teachers *know* that enables them to teach effectively? These questions will be addressed on page 14.

How Can We Improve Science Teaching?

Efforts to improve science teaching have focused on three general areas: (a) improvements in management and organization of schools, (b) preservice and inservice teacher education, and (c) science textbooks and curriculum materials. The present state of science education indicates that these efforts have so far been partially successful at best. Why is it so hard to change science teaching? What can efforts in each of these areas contribute to improvement? These questions will be addressed on page 34.

How Well Are Our Students Learning Science?

Large-Scale Studies of Student Learning

The status studies and reports are nearly unanimous in answering this question: "Not very well." Studies have cited two types of evidence:

achievement test scores and enrollment in science courses. Literature describing a crisis in science education focuses on declines in achievement test scores as a major matter of concern. Declines in Scholastic Aptitude Test (SAT) scores have received considerable attention according to a report by the National Science Foundation and the Department of Education (1980, pp. 46-47). Perhaps the best data for looking at the trend in the area of science comes from three studies by the National Assessment for Educational Progress (NAEP, 1978) and a follow-up study conducted by the Science Assessment and Research Program (Hueftle, Rakow, & Welch, 1983). Science achievement tests were administered to nationwide samples of 9-, 13-, and 17-year-olds at four different times over the past 15 years. The results of those test administrations are summarized in Table 1.

A look at Table 1 reveals some clear trends. Generally small but consistent declines in achievement are evident. These declines are larger for the older students, the ones whose science knowledge comes more from school and less from other sources such as books, television, and personal experience. The current "crisis" thus consists of a long established trend that has not accelerated in recent years. However, the existence of this trend is clearly a reason for concern. A close look at how students perform on individual items shows even more reason for concern. The questions that large numbers of American students are missing just are not very hard. Even in 1969, the American population was not particularly literate in science. NAEP data could best be summarized by saying that our science education system has *never* worked very well for the majority of our students.

Enrollment in Science Courses

A second kind of data cited in support of the judgment that our students are not learning enough science relates to student enrollment in science

Table 1

Mean Scores (Percent Correct) on NAEP Science Test

Age of Students	Type of Item	Date of Test 1969-70	1972-73	1976-77	1981-82[a]
9	Content	ND	ND	ND	ND
	Inquiry	ND	ND	53.6	52.6
	Science, Technology & Self	ND	ND	57.1	59.9[b]
	Attitude	ND	ND	67.0	66.4
13	Content	55.2	53.5[b]	52.8[b]	52.4
	Inquiry	ND	ND	58.6	58.0
	Science, Technology & Society	ND	ND	56.8	57.4
	Attitude	ND	ND	57.7	55.1[a]
17	Content	66.7	63.9[b]	61.7[b]	59.7[b]
	Inquiry	ND	ND	72.2	69.6[b]
	Science, Technology & Society	ND	ND	67.5	67.0
	Attitude	ND	ND	57.8	56.3

Note: NAEP = National Assessment for Educational Progress.

[a]Data for 1981-82 were collected by the Science Assessment and Research Program (Hueftle, Rakow, & Welch, 1983).

[b]Change from previous test administration was statistically significant ($p < .05$).

ND = No data collected.

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courses. The proportion of high school students enrolled in science courses has declined steadily from 1960 to 1977 (Welch, 1979). As argued by Harnischfeger and Wiley (1976) such declines in curriculum exposure are probably major factors contributing to declining achievement. The National Science Foundation and Department of Education report (1980) concludes:

> When combined, the course enrollment patterns and achievement data discussed earlier indicate that the relatively few students who have strong interests in the possibility of science or engineering careers are learning as much science and mathematics as they ever did--perhaps even more. However, many students are ending their studies of these subjects at increasingly early stages and are scoring less and less well on achievement measures. There has always, of course, been a large discrepancy in the amount of science and mathematics training acquired by those who are interested in science and engineering careers and those who are not, but the data show that in recent years that division has been widening (page 47).

The argument that declining test scores are related to declining enrollment suggests that the reverse might also hold. Indeed, many proposals for increasing science requirements have been pushed forward, most notably in *A Nation at Risk*, the report of the National Commission on Excellence in Education (1983). This report recommends that the requirement for high school graduation be increased to include three years of science. In contrast, most school districts currently require one year of high school science (National Research Council, 1979, page 85).

The approach of raising requirements to increase enrollment and thereby improve achievement undoubtedly has merit, but we should be cautious about simply requiring all students to take more science courses. Many students may be avoiding science courses because they have learned little or nothing from the science courses that they have already taken. Thus, we need to look not only at the number of science courses that students take, but also at what students learn when they enroll in specific courses. To investigate this

issue, we will turn to the second body of research: research on classroom teaching and learning of science.

Learning from Specific Courses

A growing body of research indicates that meaningful learning in science courses is usually limited to a small minority of students. The students who are "good in science" understand while all the rest memorize. We will begin by illustrating this point with four specific examples of learning from different science courses.

What are the forces on the coin at Point B, when it is moving upward through the air?

Physicist's answer (Ignoring air resistance)

Typical incorrect answer

Typical incorrect explanation:

> While the coin is on the way up, the "force from your hand" (F_h) pushes up on the coin. On the way up it must be greater than F_g, otherwise the coin would be moving down.

Figure 1. The coin toss problem (adapted from Clement, 1982).

Example 1: The coin toss problem and college physics. The coin toss problem, illustrated in Figure 1, is a very simple application of Newton's laws of motion, which are taught in almost all high school and college physics courses. According to Newton, a coin tossed upward in the air is subject to only two forces: a downward force due to gravity and a small additional downward force due to air resistance. (In most instances, respondents are instructed to ignore any air resistance.) These forces eventually slow the coin to a stop and it begins to fall back toward the earth. Most students, however, also draw or describe an upward force on the coin, a force in the direction of motion. Furthermore, conventional physics teaching does not seem to help many students with this problem. In one study of college engineering majors (most of whom had already taken high school physics), the percentage of students answering the question correctly rose from 12% before the beginning of instruction to 28% after one semester of physics, then to 30% after two semesters (Clement, 1982). Why weren't the other students able to give the correct answer?

Example 2: The rusting nail and high school chemistry. Robert (not his real name) is a student who has completed about four months of instruction in high school chemistry, including instruction on chemical reactions. He is passing the course. When he is asked to explain what happens when a nail rusts, this is his explanation:

> The coldness reacts on it [the nail] . . . plastic doesn't rust because coldness doesn't cause the same reaction . . . rusting is a breakdown of the iron because it [coldness] brings out the rusting . . . it [coldness] almost draws it [rust] out, like a magnet . . . like an attractor it brings it out.

Robert gave similarly unscientific explanations for other chemical changes, including the oxidation of copper and the burning of a match. He

consistently indicated that he was satisfied with his explanations, that they made sense to him, and that he thought they were similar to those that would be given by a scientifically trained adult. He believed that the main deficiency in his answers was that he was not using enough scientific terminology (Hesse, in progress). How could Robert (and many students like him) be so unaffected by four months in a chemistry class?

Example 3: Food for plants and elementary school biology. Table 2 displays the answers of 4 fifth-grade students before and after a 6-week unit on "Producers" from a widely used and highly respected elementary school science program (Knott, Lawson, Karplus, Thier, & Montgomery, 1978). Students were supposed to learn through a series of experiments and discussions that plants are producers: rather than consuming food, they produce it themselves through the process of photosynthesis. Renee, Mike, and Andrea are typical of many of the students who experienced this unit. They added sunlight to their previous lists of things that they considered "food for plants." Only 7% of 213 students studied ended the unit learning the intended conception, that plants get food *only* by making it themselves (Roth, Smith, & Anderson, 1983). Why didn't the unit work for the other 93% of the students?

Example 4: Light and vision and elementary school physical science. Figure 2 shows a question from a test given to 113 fifth-grade students before and after a 5-week unit on light and vision (Anderson & Smith, 1983a). Only 6% of the students were able to answer this question correctly before the unit began. The others showed no awareness that the boy sees by detecting light reflected off the tree. At the conclusion of the unit, 24% of the students answered this question correctly. Why didn't the other 76% learn about the role of reflected light in seeing?

Table 2

Students' Answers to the Question, "Describe What Food is For Plants" Before and After Instruction on Photosynthesis

Student	Pretest	Posttest
Renee	Fertilizer, water	Water, fertilizer, light
Mike	Fertile rich soil	Soil is a food for plants, fertilizer, sun, water
Karin	I don't know	The cotyledon and sunlight and the minerals in the soil
Andrea	Plant food, water, sunshine	Water, dirt, soil, sun (they need it for energy and their making of food)

This boy sees the tree.
Draw arrows to show how the light travels so that he can see the tree.

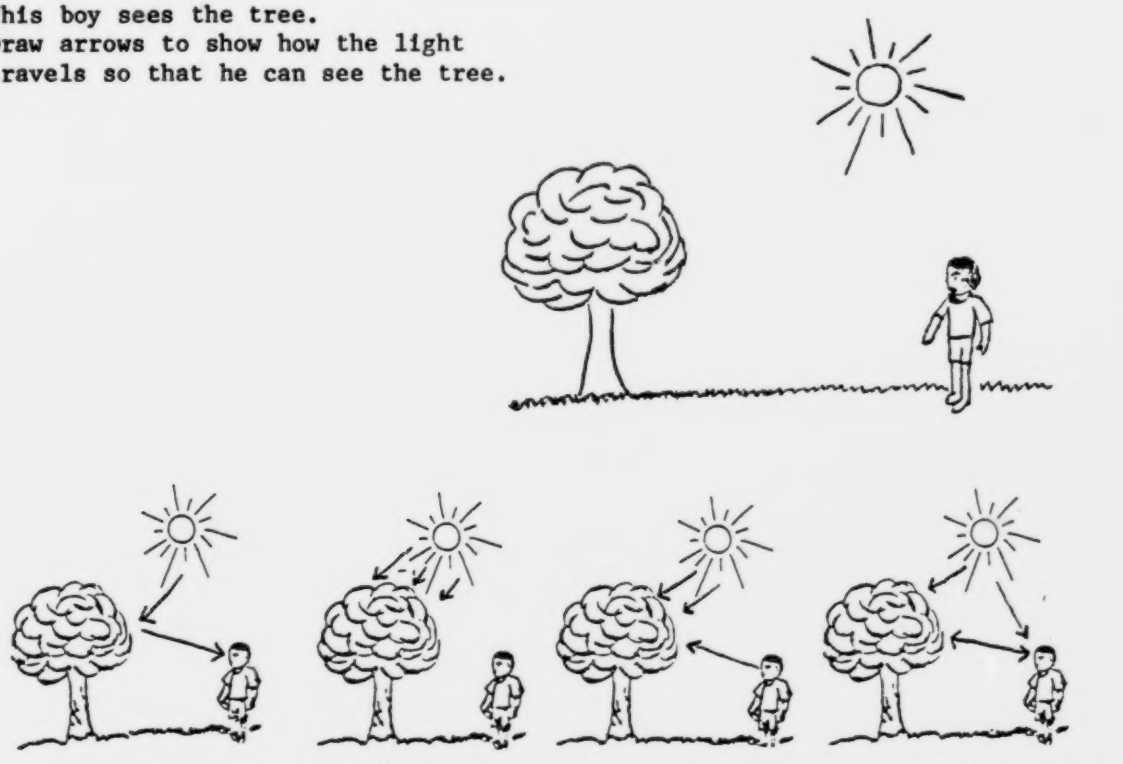

Figure 2. Percentage of students with various pretest answers to the boy and tree problem.

Implications. Results like those cited above have been documented in dozens of studies covering all scientific disciplines (Driver & Erickson, 1983; Helm & Novak, 1983). Students who successfully memorize formulas and pass courses still fail to apply scientific concepts even to relatively straightforward problems, especially if those problems involve objects or situations that students know from everyday experience. The researchers engaged in these studies have generally been less interested in documenting the extent of failure than in understanding why students fail. It is for their insights into this question that this body of research is most valuable.

Why Is Science So Hard to Learn?

The students described above might have failed to learn because the teaching was bad. However, research on teaching and learning of science has documented many examples where students persist in giving incorrect answers in spite of teaching that is "good" by any reasonable standards. Furthermore, patterns in those incorrect answers suggest another reason that students might stay committed to their incorrect answers.

Those incorrect answers make sense to the students. Cars, balls and other objects in our everyday experience come to a stop unless something is done to maintain their motion, so doesn't any motion require a force? We know that nails rust when they are left in cold, damp places, so isn't coldness responsible for the rusting process? We know that *we* get food from a variety of sources; why not plants, too? Can't you buy plant food in the store? Don't we say "I see the tree" rather than "I see the light reflected by the tree?"

In general, there are consistent understandable patterns in the incorrect answers that students give to questions like those in the examples. Researchers in this area attribute these patterns of incorrect answers to knowledge

structures which are described by a variety of terms, including misconceptions, naive theories, preconceptions, preconceived notions, and alternative frameworks. Although there are differences among the meanings that researchers attach to these terms, the similarities are more important. An awareness of these alternate theories and their importance has arisen because of parallel revolutions in philosophy of science and cognitive psychology.

Philosophers and historians of science such as Stephen Toulmin (1972) and Thomas Kuhn (1970) have studied how scientists develop new theories and how those theories come to be accepted by a scientific community. Contrary to most earlier views that theory emerges logically from data, they view theory as creative invention which defines questions, points toward relevant data, and provides the basis for interpreting or giving meaning to data. Prolonged failure of a theory to raise interesting questions or adequately explain data creates conditions favorable to the development of new theories. Rather than simply adding new knowledge, the successful emergence of such alternatives has profound effect on what scientists do, how they do it, and even on what they define as "knowing."

Piaget (Furth, 1969) and many contemporary cognitive psychologists view human thinking as theory-dependent in much the same way. We understand and act on our world in terms of our current theory-like knowledge structures or conceptions. They direct us to seek certain information and provide the basis for interpreting the information we encounter. They provide our immediate options for acting in the world. They are thus the basic mechanisms by which we understand or comprehend. Toulmin (1972) called attention to the parallel between knowledge growth in science and in individuals, referring to "the problem of conceptual change."

Thus students spontaneously construct theories which help them to interpret familiar phenomena before they begin formal science instruction. These naive theories are usually understandable and sensible; they are in accord with common experience and everyday language, and they provide reasonable explanations of what we see around us.

An awareness of these naive theories, however, leads to a very revealing description of what must happen when students learn science. They cannot simply add new knowledge to what they already know. Instead they must abandon habits of thought that they have used successfully for many years in favor of new, more complex, and often counterintuitive ways of thinking. No wonder learning science is so hard!

Conceptual Change and the Science Curriculum

This view of science learning also has important implications for the science curriculum. Rather than treating the science curriculum as a set of facts, concepts, or theories that students must master, a conceptual-change view of learning implies that the curriculum consists of a few major conceptual changes that students must undergo, accompanied by a great deal of "filling in the details." The detailed facts, concepts, and theories of science are meaningful to students only if they can be placed in a meaningful conceptual context.

One of the most valuable contributions of a view of learning as conceptual change is the insight it provides into the nature of learning with *understanding*. This is learning in which students abandon naive conceptions and adopt more scientific alternatives. For students who fail to change their naive conceptions the only alternatives are to memorize new information without understanding--what Ausubel (1968) calls "rote learning"--or misinterpret that information in terms of their naive misconceptions. Thus teaching that

allows students to retain their naive conceptions is doomed to produce only misunderstanding or rote memorization. The available evidence indicates that such teaching is all too common in our schools.

Why does such teaching persist? If science teachers want their students to understand (as most teachers surely do), then why do so many students continue to memorize or misunderstand? In order to answer these questions we turn to research on the background and the behavior of science teachers.

How Competent and Well Prepared Are Science Teachers?

As in the case of student learning, the status studies and the research on science classroom teaching have investigated teacher competence and preparation in quite different ways. As a result, they produce different but complementary types of information. The status studies have looked at teachers' feelings about their own competence and at their professional education and background. The studies of classroom teaching have focused on the actual performance of teachers in science classrooms.

Results from the Status Studies: Teachers' Science Backgrounds and Personal Judgments

Considerable attention has been focused on the science content preparation of teachers who are currently teaching science at the elementary and secondary levels. Science is increasingly being taught by teachers without majors in the subjects they are teaching. For example, nearly half of those teaching chemistry in Michigan during 1982-83 did not major in chemistry. Nearly two-thirds of those teaching physics did not major in physics (Hirsch, 1983). Nationally, more than three-fourths of the states reported shortages of general science, chemistry, and physics teachers during the 1981-82 school year. Of those newly hired to teach high school mathematics or science in 1981-82, half were unqualified and were teaching with emergency certificates (Hurd, 1982).

At the elementary level, where few teachers have science majors or minors, only 22% of the teachers judge themselves adequately prepared to teach science. In contrast, 67% judge themselves adequately prepared to teach reading (Weiss, 1978; National Research Council, 1979).

These data point toward a need for increased emphasis on both preservice and inservice teacher education in science. The extent of the problem is probably *understated*. We can accept that teachers who say they have an inadequate background or who lack science content knowledge are *not* adequately prepared, but is the converse true? Are self-confidence and science content knowledge enough? What other kinds of knowledge do science teachers need?

To answer these questions we turn from the status studies to investigations of classroom teaching and learning in science. If we can identify and study effective science teachers, then we can understand better what they do that makes them effective and what knowledge they need to perform effectively.

Defining and Describing Effective Science Teaching

Our discussion of classroom research on effective science teaching begins with a question that all researchers on teaching effectiveness must deal with in one way or another: How do we tell good teaching from bad? The performance of teachers can be judged by many different criteria which lead to different conclusions about what effectiveness is. Therefore, we begin by stating and defending our position, admitting that other criteria could lead to other conclusions about effectiveness.

Our definition of effective science teaching focuses on the learning problem that we identified as critical in the previous section: the problem of conceptual change. At a minimum, science teaching must help students overcome naive conceptions or habits of thought and replace them with scientific

concepts and principles. If teachers fail to achieve this minimal goal, then misunderstanding or rote memorization is inevitable.

This definition makes it possible to investigate effective science teaching empirically. The techniques developed by researchers into student scientific thinking (see page 3) can be used to identify critical conceptual changes that must take place if students are to understand a scientific topic. Then various teaching techniques can be tried, and the most successful can be described.

A small number of studies describe such empirical investigations. Most of these studies involved development of instructional procedures and materials designed to address specific naive student conceptions and to develop alternative scientific conceptions (Anderson and Smith, 1983b; Minstrell, 1984; Nussbaum & Novick, 1982; Roth, Anderson & Smith, 1986). These efforts were much more successful than conventional instruction in bringing about conceptual changes in students. In each instance the authors described features of their successful instruction which contrasted with the less successful conventional instruction.

But how can the essential features of teaching for conceptual change be described? One kind of description focuses on teachers' classroom behavior: They asked certain kinds of questions, spent a certain percentage of their time in laboratory activities, and so forth. A strictly behavioral approach to describing teaching for conceptual change does not work very well. Some of the most important characteristics of conceptual-change teaching concern cognitive issues such as how teachers decide what to do in a classroom, or how students think about what is happening. Therefore, our description of effective teaching for conceptual change operates at three different levels:

1. Student thinking. One kind of description of successful teaching focuses on how students think when they are undergoing conceptual change.

Successful teaching is then defined as whatever helps students think appropriately.

2. Teaching strategies. Knowing how students should be thinking is not the same thing as actually making it happen. An adequate description of successful instruction must also include what happens in classrooms, what teachers *do* to promote appropriate thinking.

3. Teacher knowledge and skills. The study of teachers' performance ultimately leads us back to a question posed earlier in this section: "What is the knowledge that underlies effective performance?"

Describing Effective Teaching in Terms of Student Thinking

One way of trying to describe what effective teaching consists of is to watch the *students* rather than the teacher. What are they doing and thinking when someone is teaching well? What are they doing and thinking when teaching is ineffective? Our answers to these questions are far from complete, especially at the critical level of student thinking. Even the students themselves are not fully aware of all their thoughts, and those thoughts are inevitably modified by any attempt to verbalize or describe them.

Nevertheless, there are some useful partial answers. Perhaps the best of these is that of Posner, Strike, Hewson, and Gertzog (1982). They suggest that, if instruction is to produce basic changes in students' conceptions, it must meet the following criteria:

1. Students must become dissatisfied with their existing conceptions.
2. Students must achieve a minimal initial understanding of the scientific conception.
3. The scientific conception must appear plausible.
4. Students must see the scientific conception as fruitful or useful in understanding a variety of situations.

These criteria are quite useful in understanding why some teaching strategies seem to work and others do not. The teaching strategies that work include elements that help students achieve all four criteria. The teaching strategies that do not work generally give students little or no help in achieving some of the criteria.

Describing Effective Teaching Strategies

A second way of describing effective teaching for conceptual change is to focus on teachers and what they do in the classroom. What teaching strategies or patterns of behavior contribute most to effectiveness in teaching for conceptual change? In summarizing the results of classroom studies that addressed this question (Roth, Anderson & Smith, 1986; Minstrell, 1984; Nussbaum & Novick, 1982; Roth, 1984), we focus on how effective teachers for conceptual change accomplish three tasks that confront all science teachers: presenting information, using demonstrations and laboratory activities, and questioning.

Presenting information. A first response of many teachers to research findings that students have not learned a particular scientific conception is to ask, "Why not just tell them--explain the scientific conception to the students?" One answer to this question is, "That's what we usually do and it usually doesn't work." Much instruction, especially at the secondary and postsecondary levels, consists of presenting information. Lecture, lecture/discussion, and having students read textbooks are the primary activities of teaching at those levels. Such presentations almost always include information that students are subsequently found not to have learned or understood. Why don't conventional presentations of information work?

The problems with most presentations to students arise from the teacher's failure to take students' naive conceptions into account. An individual's

conceptions serve as the organizing and interpretive framework for new information. Therefore, presentations of detailed information organized according to the scientific conception are not comprehended or are misinterpreted by students who hold naive conceptions. For example, explanations of color vision in terms of the relative absorption and reflection of different colors of light make little sense to students who believe that we see by perceiving objects directly. (See Example 4, page 9.) Understanding this explanation of color vision depends upon the underlying conception of vision as the detection of light reflected from objects.

Students can understand detailed scientific information only if they understand basic scientific conceptions. However, simply stating the scientific conception is hardly ever sufficient to bring about conceptual change. For example, instruction in Newtonian mechanics almost always includes explanations of Newton's First Law: Objects in motion tend to stay in motion unless acted upon by some force. Nonetheless, many students leave such instruction with the contrary notion that motion cannot continue without a force. (See Example 1, page 8.)

Another question often comes from teachers, primarily at the elementary level, who have a strong commitment to hands-on or discovery approaches to teaching. Such teachers tend to ask, "Should we *ever* come right out and tell the students answers?" Briefly, the answer is "yes." One of the requirements for conceptual change (from the naive conception to the scientific conception) is that the students develop an initial minimal understanding of the scientific conception (Posner et al., 1982). Because students usually cannot come up with these conceptions on their own, some presentation of such new conceptions is essential (Atkin & Karplus, 1962; Smith and Anderson, 1984). In each of the successful instances of conceptual change that we reviewed, the scientific conception was directly explained to the students.

It seems that presentation of scientific concepts is necessary, but it is usually done in ways that do not work. The classroom studies, however, also provide examples of ways of presenting information that *did* work. What did the teachers do right in those situations? Let's look at an example.

In Example 4 above, we showed that most fifth-graders do not understand the role that reflected light plays in seeing. How can we tell students that we see by detecting the light that objects reflect? One approach is incorporated into the textbook (Blecha, Gega, & Green, 1979) the students were using in classrooms that we observed:

> Bouncing Light
>
> Have you ever thrown a rubber ball at something? If you have, you know that when the ball hits most things, it bounces off them. Like a rubber ball, light bounces off most things it hits.
>
> When light travels to something opaque, all the light does not stop. Some of this light bounces off. When light travels to something translucent or transparent, all the light does not pass through. Some of this light bounces off. When light bounces off things and travels to your eyes, you are able to see. (p. 154)

Simply having the students read this passage was not very successful. Only 20% of 113 children in the five classrooms using this text came to understand seeing as detecting reflected light (Anderson & Smith, 1983a).

In contrast, consider another way of presenting similar information. Figure 3 illustrates one of a set of 13 overhead projection transparencies made available to the same teachers in the second year of the study. Each transparency first presents a situation and a question calling for an explanation. An overlay presents the scientific conception in the form of an answer to the question.

Using these transparencies and the accompanying information, the teachers were able to help 78% of the students come to understand seeing as the

detection of reflected light, a threefold increase over Year 1 (Anderson & Smith 1983a). What accounts for their improvement? One of the major changes between the two years was the nature of the teachers' presentations of the scientific conception.

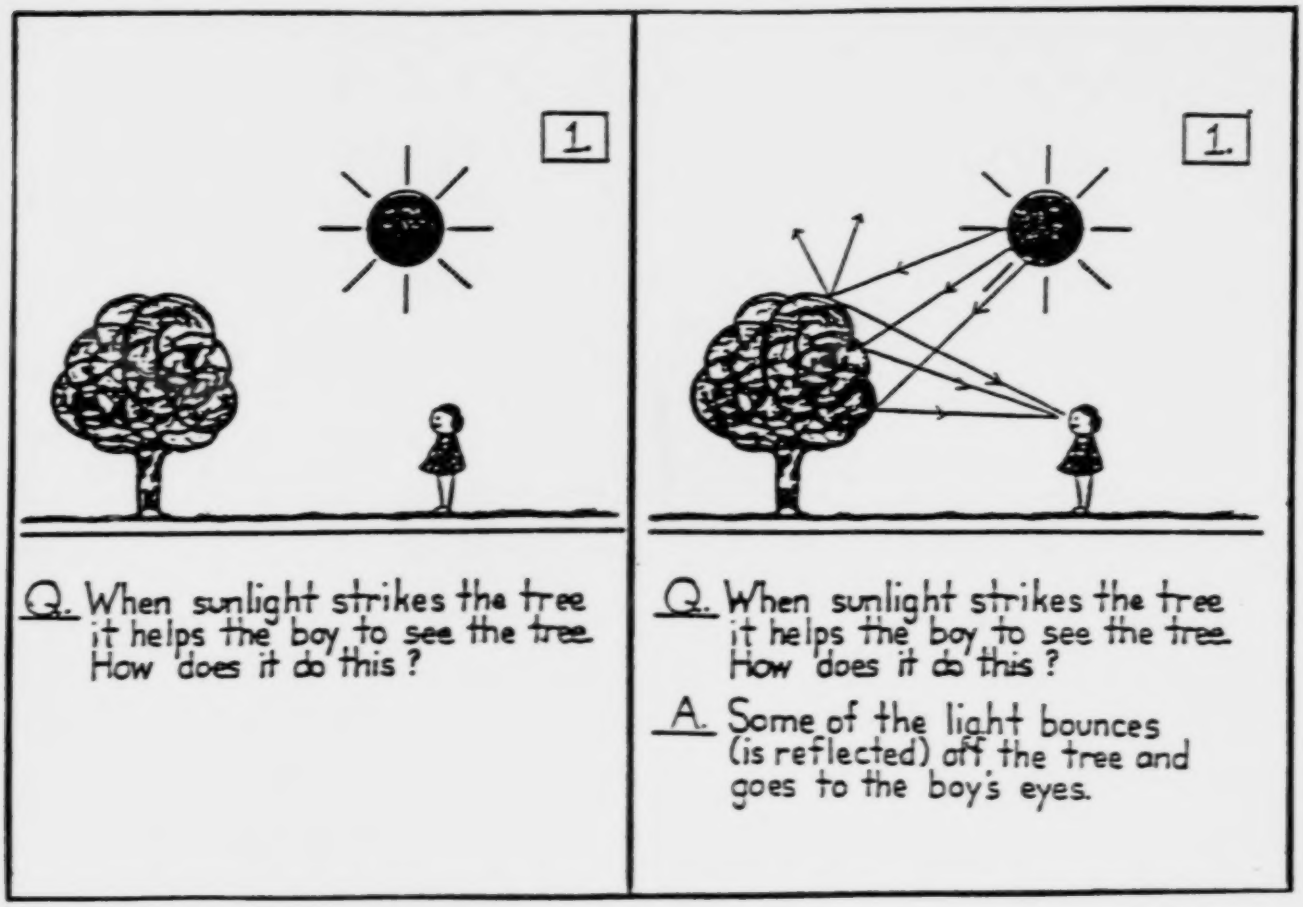
1
Q. When sunlight strikes the tree it helps the boy to see the tree. How does it do this?
1.
Q. When sunlight strikes the tree it helps the boy to see the tree. How does it do this?
A. Some of the light bounces (is reflected) off the tree and goes to the boy's eyes.

Figure 3. Overhead transparency presenting a scientific explanation of the role of light in seeing (Anderson & Smith, 1983a).

The question posed in Figure 3--How does the light help the boy see the tree?--typically elicits responses reflecting student misconceptions. Thus, students see the contrast between their own answers and the scientific alternative presented in the overlay. This kind of contrasting was common to the

presentations of scientific conceptions in all the successful teaching instances (Anderson & Smith, 1983b).

Another feature of this example was also common to the successful instances. The presentations of a scientific conception either involved, or was immediately followed by, the application of the conception to a specific phenomenon (in this case seeing a tree). This provided the teachers opportunity to diagnose problems in student comprehension and give them corrective feedback.

In the successful instances of teaching for conceptual change, the presentations of the scientific conceptions were also emphasized and distinguished from less important auxiliary information. The key scientific conceptions were not presented as simply one fact among many. These presentations, along with opportunities for application and feedback, were typically repeated several times. The importance of such repetition was expressed by several researchers (Roth, 1985; Minstrell, 1984; Smith & Anderson, 1984).

These three features of presentations of scientific conceptions--direct contrast with student misconceptions, immediate application to explaining a phenomenon, and explicit emphasis with repetition--were common to the successful instances of teaching for conceptual change. These features apparently helped meet the requirements that students achieve a minimal initial understanding of the new conception and find it plausible (Posner et al.'s, 1982 criteria 2 and 3).

Laboratory Activities, Demonstrations and Applications: Relating Concepts to Phenomena

Laboratory and "hands-on" experiences are widely advocated for the teaching of science. Laboratory activities are a part of many secondary school and college science courses, and most elementary school science

programs include recommended hands-on activities. Are hands-on activities essential or important for student learning in science?

Answering this question requires that distinctions be made among the various kinds of things that are learned in science. Skills in performing science processes such as making measurements and manipulating laboratory apparatus can be practiced only with direct experience with appropriate materials and phenomena. For learning science content, however, the answer is less clear cut. The results of the studies of student learning described earlier show that traditional science laboratory activities are *not* very useful for helping students undergo conceptual change.

Hands-on activities of some sort played an important role in all the studies of successful teaching for conceptual change. As with presentation of scientific information, teachers who want to teach for conceptual change must ask not *whether* to use laboratory activities but *how* to use them. In fact, a focus on hands-on or laboratory activities is probably too narrow. In more general terms, successful teaching for conceptual change provides students with many opportunities to relate the scientific concepts they are studying to real world phenomena through laboratory activities, demonstrations, audiovisual aids, and discussions of familiar phenomena.

One use of phenomena common to the successful instances of conceptual change teaching was described in the previous section. Applications of newly presented scientific conceptions to specific phenomena were used to diagnose student misconceptions and provide corrective feedback and to contrast scientific and naive explanations. The phenomena used were often familiar everyday events. Use of such phenomena helps students realize that science applies to their world, not just to exotic "scientific" phenomena. The phenomena help the students come to view the scientific conceptions as plausible.

Several researchers (e.g., Nussbaum & Novick, 1982) have proposed challenging students' naive conceptions with "discrepant events," phenomena with results contrary to student expectations. For example, contrary to most novices' predictions, a pad of steel wool gets heavier when it "burns up" (Driver, Child et al., undated). Such events do not automatically undermine students' naive conceptions since conceptions, like scientific theories, can be fixed up to account for almost anything (Hewson & Hewson, 1984). But they can be useful in creating dissatisfaction with students' naive conceptions (Posner et al.'s, 1982, Criterion #1), especially when the scientific conception is shown to explain such events with relative ease. This contrast can also enhance students' sense of the usefulness of the scientific alternative (Criterion #4).

Not only discrepant events but also familiar, everyday events can be used to challenge students' naive conceptions. Students' naive explanations of familiar phenomena often have shortcomings which the students can grasp when they are pointed out to them and contrasted with scientific explanations. For example, in another of our overhead transparencies for the unit called *Light*, a girl is shown standing on the opposite side of a wall from a car. The question is posed, "Why can't the girl see around the wall?" A typical answer is, "You can only see in straight lines." This answer is essentially another way of saying, "You cannot see around things" and is thus circular reasoning. *Why* can we only see in straight lines? The difficulty students have in answering this question in terms of the naive conception contrasts with the straightforward scientific explanation provided on the overlay to the transparency: "Because light reflecting from objects travels in straight lines; it cannot curve around objects to our eyes." The shortcoming of the naive conception contrasted with the success of the scientific alternative makes this use of an

everyday phenomenon effective in both creating student dissatisfaction with their naive conception (Posner et al.'s, 1982, Criterion #1) and enhancing their sense of the fruitfulness of the scientific alternative (Criterion #4).

We have discussed the roles of phenomena in addressing all four of the criteria for conceptual change. In all these instances, the phenomena were chosen because they set up contrasts between naive student conceptions and the scientific conceptions. However, such phenomena do not speak for themselves. For phenomena to be useful in promoting conceptual change, students must not only encounter them, but become actively involved in trying to *explain* them. In the next section we discuss how the teacher's use of questions can help this process along.

Questions and the Use of Phenomena

The asking of questions is a common occurrence in most classrooms. However, questions differ dramatically in their effects on both students and teachers. Consider the following examples:

1. True or false? Light travels in straight lines.
2. What are some things that help us to see?
3. Why can't the girl see around the wall?

What thinking is each of these questions likely to stimulate in the students?

The true-false question is from the "Test on Understanding" at the end of the unit called *Light* in a fifth-grade science textbook (Blecha et al., 1979, p. 190). Even if they understand nothing about light, many students can recognize that this statement is identical to a statement presented earlier in the text and reiterated on the previous page as a "main idea." In fact, Roth (1985) has shown that many students can answer questions like this correctly even if they remember nothing about the text at all! We found that students who had little conceptual understanding of light and vision did quite well on

this test (Slinger, Anderson, & Smith, 1983). Some "Test on Understanding"! Thus the first question, which simply asks students to recall a statement, is of little use in teaching for conceptual change.

The second question--What are some things that help us to see?--is from an introductory page of the same unit (Blecha et al., 1979, p. 145). The sample answer included in the teacher's edition is as follows: "Light shines on things and bounces off them to my eyes. My eyes send messages about what I look at to my brain. Then I see things." Students in the classes we observed seldom mentioned light and never gave any explanation, scientific or naive, of the role of light in seeing. Instead they typically talked about eyeglasses and telescopes. The second question, like the first, is of little use in promoting conceptual change. It is too vague and open ended even to lead to discussion of important issues.

Question 3--Why can't the girl see around the wall?--is posed on the overhead transparency described in the previous section. In one classroom this question led to the following discussion (Roth, Anderson, & Smith, 1986, p. 15):

Teacher: (Puts up transparency #2.) Why can't the girl see around the wall?

Annie: The girl can't see around the wall because the wall is opaque.

Teacher: What do you mean when you say the wall is opaque?

Annie: You can't see through it. It is solid.

Brian: (calling out) The rays are what can't go through the wall.

Teacher: I like that answer better. Why is it better?

Brian: The rays of light bounce off the car and go to the wall but they can't go through the wall.

Teacher: Where are the light rays coming from originally?

Student: The sun.

Annie: The girl can't see the car because she is not far enough out.

Teacher: So you think her position is what is keeping her from seeing it. (She flips down the overlay with the answer). Who was better?

Class: Brian.

Teacher: (to Annie) Would she be able to see if she moved out beyond the wall?

Annie: Yes.

Teacher: Why?

Annie: The wall is blocking her view.

Teacher: Is it blocking her view? What is it blocking?

Student: Light rays.

Teacher: Light rays that are doing what?

Annie: If the girl moves out beyond the wall, then the light rays that bounce off the car are not being blocked.

This discussion illustrates several important features of teachers' use of questions in the successful instances of conceptual-change teaching. First, the initial question asked for an explanation of a specific phenomenon. Explanation questions tend to drive student thinking beyond recall of specific facts to the application of their conceptions. The resulting responses often provide the teacher useful evidence about student conceptions. The teacher did more than simply pose the question. She followed up in ways which encouraged students to do the following:

Clarify and complete their explanations

Compare alternative explanations

Contrast specific aspects of the naive and scientific explanations

Construct a scientific explanation in their own words

As reflected above, the teacher's use of explanation questions in conjunction with phenomena is an important aspect of teaching for conceptual

change. Explanation questions can be usefully posed under several different kinds of circumstances to serve several different functions in teaching for conceptual change:

1. Diagnosis of student conceptions. When the teacher needs to assess the students' naive or current conception, explanation questions are especially useful for generating data for such diagnoses. Teachers in the successful instances often encouraged debate among students for this purpose (Anderson & Smith, 1983b; Minstrell, 1984).

2. Challenging student naive conceptions. In order to create student dissatisfaction with their naive conceptions, follow-up to explanation questions can be used to drive student thinking to confront discrepancies, contradictions, or gaps in their thinking. Such questions can lead students to recognize the need for or relevance of a new conception (Posner et al.'s, 1982, Criterion #1).

3. Diagnosing and correcting problems with student interpretation of a new conception. The posing of an explanation question immediately after the introduction of a new scientific conception drives students' thinking to use their new conception. This provides the teacher with a basis for diagnosing problems in students' interpretations and providing corrective feedback.

4. Applying the scientific conception to new phenomena. This helps students to see that it is useful in a variety of situations (Criterion #4). Such applications also help students to understand auxiliary facts and ideas that may be important. They also serve as a basis for continuing to challenge the naive conceptions or clarify scientific conceptions, if this is necessary.

Describing the Knowledge Needed for Effective Teaching

Use of the strategies described above leads to superior student learning, especially when conceptual change learning is considered. These strategies,

however, are rarely used in most science classrooms. Why not? The answer to this question, we believe, is that most teachers do not know how to teach this way. But what is it that teachers need to know? In answering this question we present the third part of our description of effective science teaching.

Successful teaching for conceptual change depends on two kinds of knowledge. Teachers must have both a proper orientation toward teaching and learning and a good deal of specific information about the content and students that they are currently teaching.

Teacher's orientations toward science teaching and learning. In our research we have described four general patterns of thought and behavior related to science teaching and learning. Of the four, only the pattern that we have labeled conceptual-change teaching generally produces conceptual change in students. The four patterns are described below.

1. Activity-driven teaching. We have observed this orientation primarily among elementary school teachers who are uncomfortable teaching science. These teachers focus primarily on the activities to be carried out in the classroom: textbook reading, demonstrations, experiments, answering questions, and the like. These teachers are unsure how specific activities should contribute to student learning. They try to follow the recommendations of the authors of their textbook or teacher's guide as closely as possible, assuming (or hoping) that student learning will result. Unfortunately, this hope generally is not realized. In fact, because they frequently do not understand the rationale for suggested activities, activity-driven teachers often unknowingly modify or delete crucial parts of the program, making learning of the scientific theories almost impossible for their students (Olson, 1983; Smith & Sendelbach, 1982).

2. Didactic teaching. We have observed this orientation toward teaching far more commonly than any other among teachers at all levels. Teachers with this orientation treat the teaching of science primarily as a process of organizing and presenting content to students. They expect the students, in turn, to study and to learn the content. Since they focus on presenting content rather than on student thinking, they generally fail to see that their students have misconceptions or that those misconceptions affect students' understanding. Consequently, most students remain committed to their misconceptions (Slinger, Anderson & Smith, 1983; Eaton, Anderson & Smith, 1984).

An important factor in perpetuating didactic teaching is that didactic teachers seldom ask their students the right kinds of questions. Recall questions (e.g., "What is the chemical formula for photosynthesis?") provide teachers with no hint about the existence or the nature of their students' misconceptions. Students can also answer recall questions without ever understanding that the questions are about topics of interest to them. Photosynthesis, for example, is not just "about" chemical formulas, it is also about how plants get their food. Thus didactic teaching and the asking of recall questions tend to be combined in a self-perpetuating cycle.

3. Discovery teaching. Some teachers using activity-based programs try to avoid telling their students answers, encouraging them instead to develop their own ideas from the results of experiments. They ask their students to interpret their observations in open-ended ways, assuming that the performance of the experiments will eventually lead students to develop the appropriate scientific conceptions. In the absence of direct information and feedback from the teachers, however, students generally use their own misconceptions as the basis for interpretation of activities and experiments (Roth, 1984; Smith & Anderson, 1984). Again, the result is that students remain committed to their misconceptions.

Often associated with discovery teaching is an emphasis on the importance of learning science processes: skills such as observing, measuring, making inferences, and so forth. The argument goes that students' most important learning from doing experiments is not conceptual but procedural; in doing experiments they are learning and practicing science process skills.

This argument ignores the interdependence of process and content in science. Scientists developed process skills not because those skills were important for their own sake, but because they wanted to understand better how the world works. Thus the pursuit of conceptual understanding is what gives meaning to process skills, and students who practice process skills without gaining conceptual understanding are engaged in another form of rote learning.

4. Conceptual-change teaching. In the earlier parts of this section we described some teaching strategies associated with what we call conceptual-change teaching. Teachers can never use those strategies consistently without understanding what their students are thinking. Thus conceptual-change teaching involves both the classroom behavior described above and a pattern of thought in which the teacher continually diagnoses student conceptions, considers where they are in the process of conceptual change, and acts accordingly.

Specific knowledge needed for conceptual-change teaching. Although an understanding of the process of conceptual change and an orientation toward conceptual-change teaching is necessary for success in inducing conceptual change, we can testify from our own teaching experience that it is not sufficient. In addition to an appropriate general orientation, conceptual-change teaching must be based on knowledge specific to the topic being taught. When that knowledge is lacking, even teachers who are oriented toward conceptual change must fall back into activity-driven, didactic, or discovery behavior

patterns, all of which demand less specific knowledge than conceptual-change teaching.

Our research suggests that effective conceptual-change teaching depends on topic-specific knowledge of at least three different types: knowledge of content, knowledge of students, and knowledge of teaching strategies.

1. Knowledge of content. Teaching for conceptual change requires sound knowledge of the topic under study. Rather than viewing the content as a string of facts, as is typical of didactic teachers, conceptual-change teachers must be able to identify the most basic and important principles and organize their knowledge around those, seeing how those principles are related to other ways of understanding the world, including the students' misconceptions. The development of student understanding of these basic conceptions is the primary goal of instruction. Conceptual-change teaching strategies also require that teachers have knowledge of a range of real-world phenomena and how scientific conceptions explain them.

2. Knowledge of students. Although all of the approaches to teaching described in the previous section require a certain amount of knowledge about how students typically respond to instruction, the conceptual-change orientation to instruction is unique in requiring knowledge of the misconceptions students bring with them to instruction. Conceptual-change teachers must combine knowledge of content with knowledge of students' miconceptions to construct learning goals for conceptual-change teaching, that is, the changes in students that must be brought about through instruction.

3. Knowledge of teaching strategies. A teacher's understanding of students and the content to be taught will not assure that students will learn that content. The teacher must still make learning take place through the use of appropriate teaching strategies and classroom activities. The strategies

described earlier in this paper can be used to help students change their conceptions, but they must be used in a flexible and responsive manner. The teacher must diagnose student misconceptions and monitor student progress, then use that information to select activities that challenge student misconceptions, introduce scientific conceptions, and promote student understanding of the scientific conceptions.

Implications

For us, thinking about the specific knowledge needed for various styles of teaching helps to explain why didactic teaching is so prevalent in our schools, even among the teachers (and there are many) who are sensitive to their students' difficulties with science and concerned about the students they are not reaching. Most textbooks and other teaching materials supply information about content and suggestions about teaching strategies (sometimes sound, sometimes not) but lack specific information about student misconceptions. Developing an adequate understanding of student misconceptions is a very long and difficult process, usually requiring months or years of work on a single topic. Thus no teacher can hope to develop such knowledge for all topics in the curriculum without outside help.

For most teachers there is no outside help. A major cause for the prevalence of didactic science teaching in our schools, and the resultant disappointing student learning, is that our educational system fails to help teachers acquire the knowledge they need for conceptual change teaching.

How Can We Improve Science Teaching?

Almost everyone who has examined the available evidence agrees that our present system of science education is not working very well and change is needed. But what change is needed, and how can we make it happen? On these

issues, we have controversy instead of consensus. In this section of the paper, we join the fray, proposing our own answers to these questions.

What Change Is Needed?

In the previous section, we argued that the ineffectiveness of our science education system can be attributed at least in part to the prevalence of didactic teaching in our schools. This style of teaching is ineffective whenever student understanding depends on conceptual change. It leads to rote memorization or misunderstanding, rather than to conceptual change and true understanding.

We also described an alternate style of teaching, conceptual-change teaching. Using strategies such as those described in the previous section, it is possible and practical to help students change fundamental conceptions through classroom teaching, and thus to learn with understanding rather than memorize.

For improvement we suggest focusing on shifting teachers' orientations and teaching strategies away from didactic teaching and toward conceptual-change teaching. Such change will not take place quickly or easily. Didactic teaching is perpetuated in our schools by many conditions. In particular, most teachers lack either a general orientation toward conceptual change or specific knowledge necessary for conceptual-change teaching.

Improving Teachers' Knowledge

In the previous section, we identified four kinds of knowledge necessary for conceptual-change teaching: a general orientation toward conceptual change and specific knowledge of science content, of student thinking, and of teaching strategies. In the paragraphs below, we discuss ways teachers can be helped to acquire knowledge in each area.

Changing orientations toward science teaching. Conceptual-change teaching is a new conception of teaching for most teachers, one that is fundamentally different from the conceptions that they now hold. In other words, most teachers must themselves undergo conceptual change in order to engage in conceptual-change teaching.

With this in mind, we have found that the principles and teaching strategies described in the previous section are applicable not only to teaching of science content, but also to preservice and inservice education of science teachers. Thus, it is possible to apply the criteria of Posner et al. (1982) to the problem of helping teachers understand conceptual-change teaching. Teachers who are accustomed to teaching in another style must (a) become dissatisfied with that other style of teaching, (b) achieve an initial minimal understanding of conceptual-change teaching, (c) see it as a plausible alternative to the way they are teaching now, and (d) come to appreciate the usefulness of conceptual-change teaching in a variety of situations.

Similarly, the teaching strategies described in the previous section can be adapted to teaching teachers about conceptual change. The phenomena to which the principles of conceptual-change teaching can be applied are classroom episodes and encounters with students. Thus, teachers can learn about conceptual-change teaching by dealing with these phenomena, either directly or through indirect methods such as observations of classroom videotapes or reading of case studies. For example, having teachers do interviews to assess the understanding of their own students can be very effective in creating dissatisfaction with the way they are now teaching. Studying case studies of successful and unsuccessful teaching can help teachers see the applicability of conceptual-change teaching to a variety of situations. Lecture or sustained

verbal presentations (like this paper) will probably be useful but probably insufficient to meet all four criteria for most teachers.

Improving teachers' understanding of science content. Most elementary and many secondary teachers lack adequate academic backgrounds in scientific subjects they must teach. How can these teachers learn science content that they need? Of the possible answers to this question, none is completely satisfactory.

Taking courses at a local university is undoubtedly helpful, but probably not sufficient. Most science content courses ignore some very important issues. What is special about scientific knowledge, for instance? What aspects of scientific thinking are like our "commonsense" thinking? What aspects are different? What are the truly basic conceptions upon which knowledge in a scientific discipline is built? These questions are of peripheral interest to career scientists who must learn to work and communicate effectively within a scientific community. They are of central importance, however, to teachers whose careers will be spent communicating about science with nonscientists.

Issues such as those raised above are typically considered the province not of science courses but of specialized courses in fields such as the history or sociology of science. Science teachers, however, cannot afford to relegate them to such an obscure status. They define an essential aspect of the disciplinary knowledge upon which conceptual-change teaching in science must be built. Thus, long-term improvement in science teaching depends on reform of the science education that science teachers themselves receive.

Teachers can also gain useful knowledge of science content from sources other than university course work. Formal inservice programs or informal discussion groups that focus on topics in the school curriculum can be very

useful. So can reading. Most textbooks suggest additional reading for teachers and/or students, and teachers can benefit from both. Tradebooks written for children are often remarkably informative and helpful to teachers who need to think about science content in ways that their students understand. Magazines such as *Discover* or *Scientific American* can also provide a continuing and up-to-date source of information for many teachers.

Improving teachers' understanding of students. How can information about students such as that presented on page 4 of this paper be made accessible to practicing teachers? It certainly is not now. Most investigations of how students understand science are safely locked away in research journals that teachers never read.

We suggest two promising avenues of communication, both of which we have used in our own work. One of those is through teachers' guides and program materials. It is possible to build into program materials both descriptions of important student misconceptions and questions or activities that are diagnostically useful; that is, they help teachers to see and diagnose misconceptions in their own students. In our research, we have been successful in developing materials that have these qualities (Anderson & Smith, 1983b; Roth, 1984).

A second way that teachers can learn about students' scientific conceptions is from their own students. We have worked with both preservice teachers and practicing teachers, helping them to design interviews that assess how students understand science. Although designing such interviews is difficult, many teachers have been successful. What they have learned about their students has been revealing to them and to us. The benefits of such work can extend beyond the particular topics that the interviews focus on, for teachers can use the skills they gain to investigate student conceptions of

other topics and to grow in their general understanding of student thinking about science.

Improving teachers' understanding of teaching strategies. In the previous section, we described some of the important strategies associated with conceptual-change teaching. How can teachers learn to use those strategies? It clearly will *not* work to treat those strategies as "teaching skills" to be learned and practiced in isolation from a thorough understanding of science content and student conceptions. The strategies we described were the *responses* of intelligent and perceptive teachers to particular learning problems that they had diagnosed in their students.

It is interesting that three of the studies cited in our description of teaching strategies (Anderson & Smith, 1983b; Minstrell, 1984; Roth, 1984) documented cases in which teachers changed from didactic or discovery teaching to the use of conceptual-change teaching strategies. In none of those cases did the teachers receive any explicit instruction in the teaching strategies they were later observed using. Changes in teaching behavior were due to the introduction of new program materials (Anderson & Smith, 1983b; Roth, 1984) or to the teacher's own investigation of students' conceptions and how they could be changed (Minstrell, 1984). In all cases, the teachers were aware that they were teaching differently and attributed their changed behavior primarily to improved understanding of content and of their students' conceptions. This is not to say that explicit instruction in conceptual-change teaching strategies is never important or necessary. Sometimes it is, especially with preservice or inexperienced teachers. These teachers, however, will be able to use the strategies successfully in their classrooms only if they see them as solutions to particular problems in student learning, rather than as scripts to be followed while teaching science.

Many experienced teachers are capable of using conceptual-change teaching strategies without special instruction. For these teachers, it is probably more effective to devote available resources to improving their understanding of science content and their students or to developing program materials that suggest key questions to ask and phenomena to investigate.

Other Improvements

We have devoted the bulk of this section to what we consider the single most important improvement that could happen in our system of science education, helping teachers to acquire the professional knowledge necessary for conceptual-change teaching. We conclude the section with brief discussions of other suggested changes in science education.

Improving organization and administration of schools. Many of the proposed improvements in science teaching coming from the status studies and the crisis literature (e.g., National Commission on Excellence, 1983) focus on school organization and administrative policies at the building, school district, state, or national level. Recommendations include increasing science requirements, more extensive testing of student science achievement, testing of teacher competence, incentives for recruiting or retaining qualified teachers, lengthening the school year, revising curricula, and many others.

Many of these suggestions focus on the reward systems for teachers and students. They suggest ways in which teachers and students can be encouraged, or compelled, to perform better. Such solutions are clearly of limited usefulness if teachers do not know how to perform better, if they are failing in spite of the fact that they are doing the best that they can. We have suggested that this is often the case, and in such cases, administrators must

consider their problems to be ones of knowledge dissemination or teacher education. We have suggested some approaches to this difficult task above.

Beyond that, administrators must play a role in encouraging conceptual-change teaching by teachers who do know how. Within our present school systems, changing from didactic to conceptual-change teaching entails considerable personal cost for most teachers. They must work hard to acquire knowledge that they currently lack, they must spend more time in preparation and grading, and they must face the uncertainties that come with aiming for student understanding rather than memorization. In contrast, the benefits of conceptual-change teaching, which include professional growth, personal satisfaction, and improved student understanding, tend to be delayed and not openly valued by most school administrations. Thus changes in reward systems must play an important role in encouraging conceptual-change teaching.

Reform of school curricula and curriculum materials. In this paper we have focused on the instructional effectiveness of science curriculum materials, arguing that reform is clearly necessary because so many students are learning little or nothing from their present science courses. Much of the debate about science curriculum at the national level, however, has focused on the content rather than the effectiveness of science curriculum materials. For instance, many science educators have advocated science courses that are more economically useful or that focus more on relationships among science, technology, and society (National Commission on Excellence, 1983; Harms & Yager, 1981). Although many of these recommended reforms are appropriate, changes in content are likely to be empty without improvements in teaching effectiveness. Students will merely switch from rote memorization of facts about science to rote memorization of facts about science, technology, and society.

Microcomputers and educational technology. The advent of microcomputers promises to have a substantial impact on school science. Because microcomputers and related technology are transforming our society, they affect our perceptions of what is important to teach; thus they will affect the science curriculum. In addition, science teaching will be affected by the use of microcomputers as instructional tools. Like other tools, their impact will depend on how they are used. Studies have been done that demonstrate how microcomputers can be used effectively to promote conceptual-change teaching (Hewson, 1983). A great deal of current educational software, however, promotes the use of microcomputers as tools to aid rote memorization or didactic teaching. Such programs are likely to do more harm than good.

Conclusion: What Can Individuals Do?

At this time there is a widespread public perception that science education is in a state of crisis, and there are demands for immediate improvement and reform. We suggest that, although improvement and reform are clearly needed, the metaphor and language of crisis are potentially counterproductive. We tend to think of crises as arising from sudden changes of circumstances, such as wars or natural disasters, and we respond to crises with intense but relatively short-term efforts. The present "crisis" in science education, however, has not developed suddenly. In the main, it consists of conditions that have prevailed for the last 20 years. Throughout that period our science education system has functioned relatively well for a few top students and poorly for everyone else. It continues to do so today, in spite of a long period of slow decline.

Just as the present "crisis" was a long time in the making, it will also be a long time in its resolution. The problems of science education could better be addressed by modeling our response to the curent "crisis" on deeper

and slower processes, such as the improvements in agricultural productivity and public health that have occurred over the last century. These improvements have involved the efforts of many different researchers, developers, and practitioners. They have resulted both from theoretical breakthroughs such as the germ theory of disease and from the gradual accumulation of specific knowledge, practical techniques, and technological devices. They have taken place over generations rather than a few years. Ultimately, though, they have transformed our society far more radically than any crisis or its resolution. They have vastly increased our ability to feed and maintain the health of our citizens.

Viewed from this perspective, our present problems should be viewed as an opportunity to make real, long-term improvements in science education. Such improvements, however, can only be the products of efforts by many individuals playing many different roles in the educational system. We suggest areas in which various kinds of practitioners can contribute to these long-term change processes.

Researchers and Theoreticians

Our ability to improve practice is limited by our lack of knowledge. We cannot overcome misconceptions, for example, if we do not know what they are. Deciding what is important to teach may depend on detailed analysis of an expert's knowledge or of the skills that are necessary for functional mastery of a task. Adequate understanding of many of these issues depends on the disciplined pursuit of knowledge by specialists. Research specialists must pursue these and other issues, but always with an eye toward the problems of practice. Significant research problems in science education will always be those that are clearly tied to the practice of science teaching. Researchers must also communicate their knowledge to science teachers as well as develop it.

Curriculum Developers

Most current science curriculum materials simply do not work for most students. Curriculum development in any medium--textbooks, laboratory activities, or computer software--must lead to materials that adequately meet the needs of both students and teachers. These materials must provide teachers with adequate descriptions of students' common learning difficulties and of how those difficulties might be overcome. They must also contain instructional strategies that are at least fairly well matched to the needs of students and of their teachers. Finally, materials must effectively communicate to teachers.

Teacher Educators

Teacher educators can also play a critical role in the improvement of science teaching. They can help students to understand the relationships among content knowledge, the processes of student learning, and pedagogical technique. They can provide students with at least a few successful supervised experiences in classroom situations. Most important, they can provide future teachers with a basis for professional growth by helping them to know what they need to know and by helping them learn where to find information that they lack as well as how to learn from their own teaching.

School Administrators

Administrators must also play an essential role. They can set policies that encourage students to take more science, and they must support and reward good science teaching. At one level this means being aware of what science teachers are doing and encouraging improved performance. At another level, this means helping to select the best available curriculum materials and to develop inservice education opportunities that help teachers acquire essential knowledge that they currently lack.

Teachers

Teachers must help make the support system work better for them than it has in the past. They must demand adequate inservice programs and support materials. (Publishers, for example, are unlikely to improve the quality of their materials unless they see that teachers respond by preferentially selecting those materials.) Teachers must also be aware of how small our systematic knowledge of science education is in comparison with the task that they must do, and they must develop their own personal knowledge bases. This means that teachers must become sensitive observers of their own students, learning to diagnose their students' misconceptions and evaluate how well their instruction is working. The process of development is long and slow, but the rewards in both student understanding and professional growth justify the effort.

Annotated Bibliography

The actions we suggest in this chapter would lead the reader to seek additional information. The sources identified here will help in getting started.

Descriptions of Conceptual Change Teaching

Our characterization of conceptual-change teaching was based on classroom studies. The following sources provide rich descriptions of classroom instruction and document systematic efforts to improve the effectiveness of classroom teaching.

Anderson, C.W. (Ed.) (1984). Observing science classrooms: Perspectives from research and practice (1984 yearbook of the Association for the Education of Teachers in Science). Columbus, OH: ERIC Center for Science, Mathematics and Environmental Education.

This compilation of classroom studies includes reports of two of the successful instances of teaching for conceptual change cited in this paper. Roth's chapter ("Using Classroom Observations to Improve Science Teaching and Curriculum Materials") describes a 3-year study of the teaching of plant growth and photosynthesis at the fifth-grade level. Minstrell's chapter ("Teaching for the Understanding of Ideas: Forces on Moving Objects") describes his efforts to improve student learning in his own high school physics classroom. Several other chapters also address the issue of classroom teaching for conceptual change.

Driver, R. (1983). Pupil as scientist? Milton Keynes, England: Open University Press.

This book describes students' efforts to make sense of school science. Rich with examples, it examines the metaphor of "pupil as scientist" as a way of thinking about the role of student conceptions in learning.

Roth, K.J., Anderson, C.W., & Smith, E.L. (1986). Curriculum materials, teacher talk, and student learning: Case studies in fifth-grade science teaching (Research Series No. 171). East Lansing: Michigan State University, Institute for Research on Teaching.

This analysis contrasts more and less successful cases of science teaching at the fifth-grade level. The cases deal with the topics "light and seeing" and "plant growth and photosynthesis." The analysis is summarized in terms of a set of "principles" for teacher presentations and class discussions.

Information on Students' Naive Conceptions

Research describing students' naive conceptions has been reported for a variety of science topics. The following sources will help the reader identify available research on topics or issues of interest.

Clement, J. (1982). Students' preconceptions in introductory physics. American Journal of Physics, 50, 66-71.

This article synthesizes the research on one of the most well-documented sets of naive conceptions, on the topic of force and motion. It discusses parallels between contemporary naive conceptions and conceptions from the history of science.

Driver, R., & Erickson, G. (1983). Theories in action: Some theoretical and empricial issues in the study of students conceptual frameworks in science. Studies in Science Education, 10, 37-60.

In addition to the issues discussed, this article reviews many studies. Together, this article and the next one provide a relatively complete review of research on student naive conceptions up through early 1983.

Gilbert, J.K., & Watts, D.M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. Studies in Science Education, 10, 61-98.

In addition to reviewing research on naive conceptions of several science topics, this article discusses alternative historical and contemporary definitions of the term "concept."

Theoretical Underpinnings

The following sources provide background on the psychological and philosophical foundations of student conceptions research and theoretical work on conceptual change.

Resnick, L.B. (1983). Toward a cognitive theory of instruction. In Paris, S.G., Olson, G.M., & Stevenson, H.W. (Eds.), Learning and Motivation in the Classroom (pp. 5-38). Hillsdale, NJ: Erlbaum.

This chapter describes in a historical context the "cognitive revolution" that has characterized the last two decades of psychology and then discusses recent progress on three aspects of instructional theory: (a) specification of the capabilities to be acquired, (b) description of the acquisition processes, and (c) principles of intervention.

Posner, G.J., Strike, K.A., Hewson, P.W., & Gertzog, W.A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. Science Education, 66, 211-227.

This article describes a theoretical framework derived primarily from philosophy of science that we have found very useful in interpreting our research findings. Especially useful were their "conditions for conceptual change" cited in this paper.

Cawthron, E.R., & Rowell, J.A. (1978). Epistemology and science education. Studies in Science Education, 5, 31-59.

A second area in which recent developments have influenced research on student conceptions is the philosophy of science. This article describes these developments in a historical context and discusses the views of science implicit in school science.

The National Science Foundation Studies

Helgeson, S.L., Blosser, P.E., & Howe, R.W. (1977). The status of precollege science, mathematics and social science education--1955-1975: Vol. 1. Science education. Columbus, OH: Ohio State University, Center for Science and Mathematics Education.

This report documents a review of the literature on the status of science education available in 1976-77.

Stake, R.E., & Easley, J.A. (1978). Case studies in science education (Vols. 1 & 2). Urbana, IL: University of Illinois, Center for Instructional Research and Curriculum Evaluation.

These two volumes document case studies of science education in eleven school districts across the United States.

Weiss, I.R. (1978). Report of the 1977 National survey of science, mathematics and social studies education. (Contract# C7619848, Report to the National Science Foundation). Research Triangle Park, NC: Research Triangle Institute, Center for Educational Research and Evaluation.

This report documents the results of a national survey of a stratefied random sample of districts, schools and teachers across the United States.

Responses, Syntheses and Supplements to the NSF Studies

Harms, N.C., & Yager, R.E. (Eds.). (1981). What research says to the science teacher (Vol. 3). Washington, DC: National Science Teachers Association.

This report documents an attempt to synthesize the findings of the three NSF studies of 1977-78. The authors adopted a set of broad goals representing a desired state of science education against which they compared the actual state as reflected in the three NSF studies.

National Science Foundation. (1980). What are the needs in precollege science, mathematics and social science education? Views from the Field (Report No. SE80-9). Washington, DC: National Science Foundation.

This document is a compilation of responses and recommendations from professional and support organizations following up on the NSF studies.

National Science Foundation & Department of Education. (1980). Science and engineering education for the 1980's and beyond. Washington, DC: U.S. Government Printing Office.

This is a well-documented review of the NSF studies and related research on the status of science education.

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